A Lazy-Binding Communication Protocol for Highly Dynamic Wireless Sensor Networks

Abstract

Wireless sensor networks are characterized by limited availability and reliability of the wireless channel and by high rates of node failure. These pose challenging requirements for communication protocols. Beyond these inherent limitations, node mobility and energy conserving protocols that power down nodes, introduce additional dynamics to routing protocols. Since routing performance depends on the freshness of routing or neighborhood tables, traditional state-based protocols may suffer excessive delay or packet loss (system dynamics require expensive upkeep of these tables). In this paper, a novel concept of ***Lazy-Binding*** *is proposed to cope with the elevated dynamics found in sensor networks. Based on this concept, we introduce Implicit Geographic Forwarding (IGF), the first WSN protocol that is altogether* ***state-free****. We compare our work against several established routing protocols in static, mobile and energy-conserving sensor networks under a wide range of system and workload configurations. In the presence of mobility and other dynamics, IGF demonstrates over 1000% improvement in delivery ratio and significant reduction in both end-to-end delay and control overhead. In addition, a prototype of the IGF protocol has been implemented and evaluated on the Berkeley motes platform.*

Keywords: *Sensor networks, state-free, mobility, dynamic*

1. INTRODUCTION

Wireless Sensor Networks (WSNs) continue to expand the state of the art in distributed computing. Proposed for ad hoc deployment in remote or inhospitable terrain, systems are designed to tolerate unpredictable conditions for extensive periods of time. Dynamics in sensor network topologies are increasing due to a set of new system requirements. First, these WSNs – whose applications may include military surveillance, disaster relief, environment monitoring, and smart environments – require energy conserving features to ensure system longevity [18][24]. Frequent network topology changes, due to nodes' transition into and out of the sleep state, make it crucial to maintain state freshness for communication. Second, the tiny devices comprising the wireless sensor network may be transported by the elements (e.g., wind, water, or earth tremors) or the devices may be annexed to robots or troops. These mobility factors introduce additional dynamics into network topologies. When nodes are mobile, the constant migration of nodes into and out of the communication range of one another makes it difficult to maintain freshness of routing states in the traditional state-based routing protocols. These unique challenges create the demand for a solution that can efficiently deliver end-to-end traffic in highly dynamic environments without any dependence on states in routing and neighborhood tables. Formally, we define ***state-free*** as *having no dependence on knowledge of the network topology or the presence/absence of any other node, including the states of the neighboring nodes at a particular time*. This characteristic of being state-free is valuable to sensor networks, as it supports fault tolerance and makes protocols robust to topology shifts or node state transitions. Further, a state-free solution eliminates the bandwidth-consuming packets required in state-based solutions for routing and neighbor table upkeep.

With the goals of introducing a protocol that is robust to network topology changes caused by mobility or sleep-awake transitions, eliminating the latency and overhead of state upkeep, we propose a novel concept of ***Lazy-Binding***. Lazy-Binding *defers binding volatile states as late as possible*. This enables the system to cope with the elevated dynamics found in sensor networks. Based on Lazy-Binding, we implement the first installment of this type of protocols, called Implicit Geographic Forwarding (**IGF**). IGF allows a sender to determine a packet's next-hop at transmission time. By combining *lazy-binding* and location-address semantics, IGF becomes a pure *state-free* protocol. Consequently, IGF extends location-based routing even though it has no prior knowledge of any other node in the network.

To evaluate IGF's performance, we compare our research with both classical and state of the art solutions using well-established metrics such as end-to-end delivery ratio, control overhead, and communication delay under a wide range of system configurations. Our results show the equivalent or better performance of IGF in static networks. We also show IGF's superior performance when considering mobile or energy conserving networks. In these cases we show that IGF is capable of delivering close to 100% of the end-to-end traffic while other protocols can barely delivery a tiny portion of the packets. More specifically, we note that our protocol makes two novel contributions to communication protocol design in highly dynamic sensor networks:

- A novel *lazy-binding* concept is proposed to bind routing states to the network topology just-in-time instead of tasking a specific node beforehand. This concept allows us to design the first sensor network protocol that successfully deals with continuous mobility and other high dynamic issues.

- In contrast to previous stateless solutions (GPSR [10]) which still maintain neighbor states, the IGF protocol is the first WSN protocol that is altogether *state-free*. By eliminating routing state maintenance, we save memory by discarding both neighborhood and routing tables. And we reduce congestion and energy consumption by using fewer control packets.

In the remainder of this paper we discuss our protocol and provide an in depth evaluation of our approach. After the description of the Lazy-Binding concept in section 2, we introduce IGF in section 3. Section 4 presents our experiments and analysis in mobile and other environments. Section 5 describes our prototype implementation on the MICA2 platform and its evaluations. We address related work in section 6 and conclude the paper in section 7.

2. THE CONCEPT OF LAZY-BINDING

In this section, we identify the motivation for this work and introduce the concept of lazy binding.

2.1 Analysis of the Problem

The unique characteristics of sensor networks introduce additional dynamics into the system. Network topologies and node connectivity are changing constantly because:

- Energy-conserving algorithms [18][24] require that nodes transition into and out of sleep states, and their participation in the network becomes probabilistic at any given point in time.
- Node mobility, incurred by manual or natural forces (e.g. wind, water), quickly and continuously changes the connectivity among the neighboring nodes.
- Node failure and burst interference will permanently or temporally break the wireless link.
- Incremental deployment or periodic replacement will bring new working nodes into the network and change topologies.

Although most sensor network protocols [7][10][11][12] have been developed with robust characteristics in mind, the level of fault tolerance is usually designed to adapt to occasional node failures. In order to cope with the elevated transition of network topologies, the state-based solutions are required to refresh the routing state at an increasing rate, consequently incurring more overhead and network congestion. Eventually, the performances of these algorithms might degrade dramatically, when the maintenance of the routing state can not keep up with the transition rate of the network topologies. The cases are:

- In Directed Diffusion [7], a node maintains an interest cache with gradient fields towards its neighbors. Interest entries in the cache would be invalidated quickly due to continuous mobility of sensor nodes.
- In DSR [8], any mismatch between source routing information in packet headers and available physical routes will force intermediate nodes to drop packets and incur route maintenance costs.
- GPSR [10] requires a higher beaconing rate to update the neighbors when nodes are moving in and out of each others' radio range, otherwise packets might be forwarded to nodes that are out of sender's reach.

We observe that the binding delay between the time when routing states are bound to physical network topologies and when these states are actually used for packet forwarding is the key cause of state invalidation and routing failures. A long binding delay leads to a high probability that these states will be invalid by the time they are used, especially in highly dynamic networks.

2.2 The Concept of Lazy-Binding

Due to the fact that routing states are volatile and will be outdated at a much faster rate in highly dynamic networks, it is inefficient to maintain state information *proactively* and *eagerly*. In this paper, we advocate a concept of *Lazy-Binding* to deal with this issue.

Specifically, we define **Lazy-Binding** as *deferring mapping system physics (e.g. network topologies) into volatile states (e.g. route state), required by a certain operation, as late as this operation allows.*

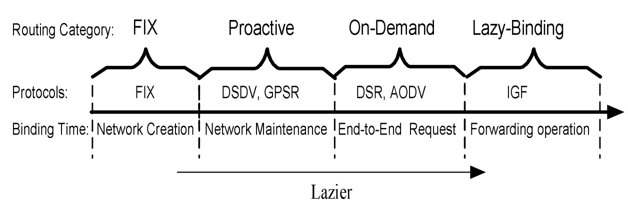


Figure 1: Binding time of different protocols

Advances in the protocol design continuously expand the ability to deal with high dynamics inside the networks. We divide these protocols into four categories (Figure 1).

1. Fix routing schemes are rarely used due to their rigid early-binding at the establishment of the network.

2. Proactive schemes such as DSDV [13] and GPSR [10] maintain the network states aggressively. Routing states are refreshed regardless whether there is need of data delivery. This eager and proactive binding property is subject to state invalidation and a high control overhead.

3. To remedy the issues along with proactive schemes, On-demand algorithms such as DSR [8], AODV [14] and Directed Diffusion [7] bind the routing state to physical topologies with a lazier approach – On-demand Route Discovery. The on-demand property allows them to defer the binding of routing states to the physical network topologies until *there is a need for end-to-end delivery*. Those schemes have been proven in [1] to be effective in dealing with moderate mobility and failures. However, binding during the route acquisition phase makes them ineffective to deal with highly dynamic networks whose topologies change at a much faster rate than the duration of connections.

4. In contrast to on-demand schemes, the IGF protocol proposed in this paper takes one step further. It defers the binding of the routing states to the physical network topology until the *packet forwarding operation actually happens at a sending node*. This design allows:
   - The elimination of communication overhead to maintain the state proactively, reducing the unnecessary update of volatile routing states.
   - The immediate detection of (i) node failure, (ii) migration, and (iii) transition into a sleep state.
   - The immediate utilization of recently awoken or newly arriving nodes.

3. IGF PROTOCOL DESIGN

In this section, we introduce the IGF protocol as an exemplar implementation of the Lazy-binding concept. In brief, IGF is a combined Routing/MAC protocol in which the location-aware nodes make forwarding decisions by lazy-binding next-hop nodes on the fly. The rest of this section is organized as follows. After the description of IGF in section 3.1, section 3.2 discusses the reason why the Lazy-binding improves IGF's performance. For the sake of simplicity, we describe IGF in section 3.1 assuming a circular radio range and a sufficient node density. The issues related to density, radio irregularity and localization error are resolved in sections 3.3 and 3.4, respectively.

3.1 IGF Details

We begin our introduction of IGF with an example. Figure 2 depicts a scenario where node S is transmitting a packet towards final destination D. We define the dark nodes within the 60 degree sector (shown in Figure 2) as *forwarding candidates* (We address the case when there are no candidates inside the specified forwarding area in section 3.3). Among these candidates, we highlight two nodes, R and A, to represent the chosen next-hop and an alternate "competing" node, respectively. In addition, gray node N represents a node within communication range of S that is not a candidate node.

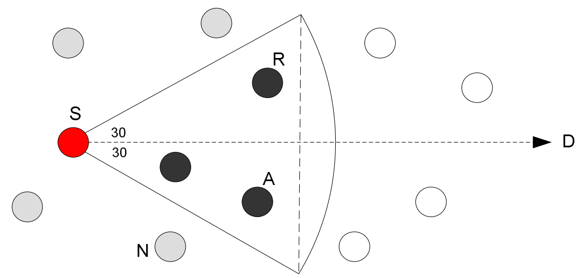


Figure 2: Forwarding Area for Source S

When node S initiates a packet transmission, the communication handshake goes through following steps: (the timeline of the IGF Handshake is shown in Figure 3)

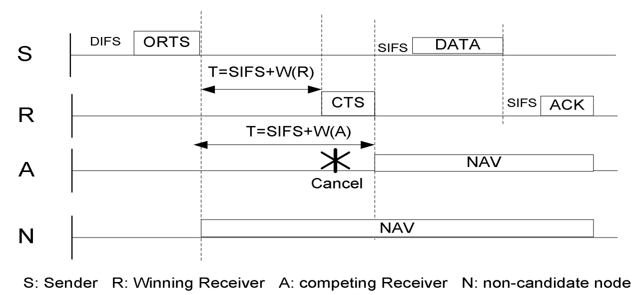


Figure 3: IGF Handshake

1. **ORTS PHASE**: With slight modifications to the 802.11 DCF MAC protocol, the IGF handshake begins when the sender S's Network Allocation Vector (NAV) timer is zero and it carrier senses an idle channel for DIFS time; S sends, via broadcast, what we call an ***Open RTS*** (ORTS).

2. **CTS-WAIT**: While all nodes within the communication radius of S receive and process this ORTS packet, only the *forwarding candidates* set a ***CTS_Response*** timer (T_{cts_wait}) that defines an appropriate amount of time that they must wait before responding to the received ORTS packet. The value of T_{cts_wait} can depend on the progress in distance towards the destination, or the energy remaining at the

potential receiver, and an additional random value. In addition, all nodes receiving the ORTS that are outside this forwarding area (gray nodes) set their NAV timer in accordance with 802.11 semantics.

3. **CTS:** While all forwarding candidates set their CTS_Response timer, only a single node, specifically the node that assigns the shortest T_{cts_wait} value (Node R in Figure 2 scenario), will respond to the ORTS with a CTS packet. To prevent multiple responses, other forwarding candidates overhearing a CTS packet will cancel their timers and set their appropriate NAV timers. In addition, the Sender S, having already received a valid CTS packet, will ignore further CTS packets heard in response to the now antiquated ORTS. We consider the IGF lazy-binding done, when sender S decides node R is the receiver for this packet.

4. **DATA:** After the Sender S is bound with a specific receiver (R), the sender S sends DATA to node R.

5. **ACK:** Node R acknowledges Sender S, if DATA is received successfully.

3.1.1 More on Forwarding Candidates

This section gives a detailed discussion on how a node determines whether or not it is a valid forwarding candidate. We define the eligible candidate according to two rules. First, we desire that a packet is propagated on a progressive path towards the ultimate destination; and second, we desire that every node within the forwarding area is capable of hearing one another, to prevent interference between forwarding candidates. As depicted in Figure 2, we choose candidate nodes that reside within a ±30-degree angle of the line connecting the Sender and final destination. Using the sender and the receiver's own location, obtained through GPS or localization schemes [6], and final destination location specified by applications at the source, we apply simple trigonometry to test the eligibility of candidate nodes.

While the first rule is intuitive, the second deserves some justification. Specifically, we desire that all forwarding candidates, responding to an ORTS packet, are within communication range of one another, to reduce the chance multiple CTS responses to a single ORTS packet. Due to the packet loss or the irregular radius, node A might still fail to know that a response to S's ORTS has already been transmitted by node R. In this case, sender S needs to resolve duplicate CTS packets by choosing only one of those responses.

As stated before, neighboring nodes that receive an ORTS, but are not within the forwarding area, simply set their NAV timer to reflect the duration of communication. This prevents collisions that result from the hidden terminal problem [3].

3.1.2 More on Setting Response Wait Times

This section provides more discussion on how to set the T_{cts_wait} value. Having determined that it is within the forwarding area of communication, a node can adopt different policies in setting its T_{cts_wait} according to metrics such as progress in distance toward the destination, the energy remaining at the receiver, probability of packet loss, processor load, single hop delay or random delay. In the current IGF implementation, we adopt following formula:

$$F = \frac{W_P * (1 - progress \,/\, radius) + W_R * rand()}{W_P + W_R}$$

$$T_{cts\_wait} = SIFS + (DIFS - SIFS) * F \quad F \in [0,1) \quad (1)$$

where *progress* is the advance in distance toward the destination. *Radius* is the nominal radio range. *Rand()* generates a random number between 0 and 1. W_P and W_R are the weights of progress and randomness, respectively. *SIFS* delay is Short Inter Frame Spacing and *DIFS* delay is Distributed Inter Frame Spacing in the 802.11 standard.

Equation (1) probabilistically allows nodes that relay packets further to wait for a smaller period of time before responding. Also, the randomization included in equation (1) can disperse the system workload among multiple equally eligible nodes. It should be noted that equation (1) is designed to be compatible with the timing rule of 802.11 DCF by guaranteeing:

- The minimum value of T_{cts_wait} is larger than or equal to the SIFS delay.
- the maximum value of T_{cts_wait} is smaller than the DIFS delay to prevent other nodes from initiating a new transmission (for a discussion of this issue see [17]).

3.2 About Lazy Binding in IGF

IGF is an extension of location-based protocols that applies lazy binding. In location-based protocols such as GPSR, routing depends on up-to-date local neighborhood tables. Normally the neighbor table is updated through periodic beaconing. The binding of a specific forwarding node to a certain geographic location is eagerly established when neighboring nodes exchange beacons. This eager-binding would be invalid quickly due to node mobility[1] or power-down, which lead to stale routing information and unnecessary beacon exchange. In addition, this eager binding is not synchronized with the packet forwarding operations. If the chosen forwarding node of a sender fails or moves out of range, the MAC layer of the sender drops

[1] Theoretically, links used in GPSR have more than 50% chance to break in the presence of mobility. See Appendix A for proof.

this packet and notifies the network layer about the routing failure. The network layer has to resolve this failure by attempting another backup route if available, which might be invalid too, or waiting until the update of the neighbor table, suffering latency proportional to the beacon period in a scale of seconds.

In contrast, IGF adopts lazy binding to discover the next hop on the fly. The worse case back-off delay introduced by lazy binding is tens microseconds according to the 802.11a standard and our implementation. This is at least 4 orders of magnitude shorter than the period of neighbor table update through beaconing found in other protocols.

In addition, route maintenance found in Directed Diffusion [7], DSR [8], AODV [14] and LAR [11] normally takes at least ten milliseconds or even seconds to fix a broken link (depending on the size of network and the cause of failure). In contrast, IGF binds the node that is able to forward the packets, right before (about 50us) the actual forwarding operation happens. This lazy binding property dramatically reduces the chance that packets are forwarded to a node that fails or moves out of range. As a result, IGF shows over 1000% performance improvement in delivery ratio when compared with several classical and state of the art solutions in dealing with high rate of network topology changes.

3.3 Optimizations for Sparse Networks

IGF targets sensor networks in which greedy forwarding is proven to be a good enough solution [22]. However, we acknowledge that without the capability of circumventing voids (e.g., the absence of forwarding candidate nodes), IGF will result in communication failure in sparse sensor networks. To improve delivery ratio, IGF has a forwarding area shift. This works when a void is detected through the MAC layer notification of failure. The network can then retransmit the packet, requesting a 60 degree up/down shift of the forwarding area to "search" for an available receiver. Those shifts allow IGF to utilize the communication area outside of the initial forwarding area. With this optimization, in the empirical study later shown in evaluation, IGF achieves a 100% delivery ratio as long as the node density is larger than 10 per nominal radio range.

It should be acknowledged that our current scheme of void avoidance can deal with void problem, however does not guarantee finding a path. Another extension of IGF, based on GPSR [10] which does guarantee that a path will be found if one exists, is to shift the forwarding area counterclockwise to find the next hop. Thus the solution follows a "right-hand-rule" when a void is detected. Since void avoidance is not focus of this paper, we leave this extension as the future work.

3.4 Design Issues

This section completes our approach with several practical design issues.

3.4.1 Radio Irregularity

For the sake of clarity, IGF is described with a nominal symmetric radio range. However, IGF does work with asymmetric irregular range. First, we enforce a symmetric channel between sender and receiver by an ORTS-CTS-DATA-ACK handshaking procedure; second, though it is possible that an asymmetric channel among forwarding candidates still exists and introduces multiple CTS responses to a single ORTS, the sender can resolve duplicated packets by simply choosing one and ignoring the others.

3.4.2 Localization error impact

IGF can be regarded as an extension of location-based protocols, whose performance can be affected by localization errors. Results from [6] show that the performance of the Geographic Forwarding (GF) protocol degrades when the localization error increases. In evaluation section 4.6, we demonstrate our IGF scheme suffers no performance penalty in delivery ratios in the presence of half radio range errors.

3.4.3 Energy implications

The 802.11b standard allows a node to turn off the radio after this node overhears a RTS packet that is not targeted to itself. IGF requires forwarding candidates to remain in listening mode to overhear the CTS for about 5×10^{-5} seconds. This requires slightly more energy; however, it is negligible compared with a high delivery ratio, few control packets and a smaller end-to-end delay we obtain.

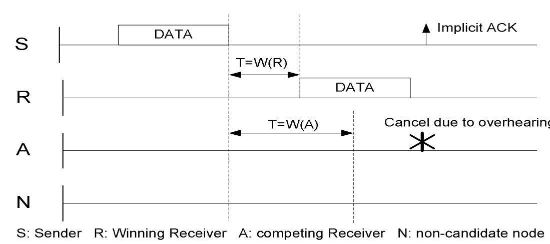


Figure 4: A MAC Scheme with Implicit ACK

3.4.4 Alternative MAC implementation

Without loss of generality, IGF is currently built and evaluated on top of 802.11 DCF. However, we note that IGF is not bound to 802.11 DCF and can be implemented with small modifications to several existing protocols. For example, IGF can be built on the MAC protocol suggested in [20] with the implicit ACK. In this scenario, forwarding candidates wait for a random delay before starting to relay the packet, and the one with smallest delay forwards the data packet. This data packet serves as both an acknowledgement to the sender and a cancel signal to the rest of the forwarding candidates. (The handshaking sequences are shown in Figure 4). We have built a prototype system on the Berkeley mote platform and evaluated it in section 5.

3.4.5 *Lazy-Binding of ID-Based Protocol*

In this paper, IGF assumes a localization service based on the fact that location-awareness is always required by sensor network applications in order to make sensor data meaningful. However, we note that *Lazy-Binding* is a general concept to deal with high dynamics in networks and its applicability doesn't depend on location service. It is promising to apply lazy-binding to ID-Based protocols such as Directed Diffusion [7]. To extend [7], we can keep the hop-count-to-a-sink as non-volatile state with respect to node failures and lazy-binding the parent of each node. We note that in ID-based case, the state-free property is not maintained, however the lazy-binding, which is independent of state-free, is still beneficial to deal with the failure of parent nodes. Due to space limitations, we can not explain all the implications and leave it as future work.

4. EXPERIMENTS & ANALYSIS

To assess the performance of the IGF protocol, we implement it in GloMoSim [25], a simulator for wireless sensor, ad hoc, and mobile networks. GloMoSim provides a high fidelity simulation for wireless communication with detailed propagation, radio and MAC layers.

4.1 Simulation Settings Overview

To make our evaluation close to existing hardware proposed for use in WSN environments [21], we set our system parameters as shown in Table 1.

Table 1: System Parameters

Parameters	Setting
Nominal radio Radius	40 meters
Bandwidth	200 kbps
Packet Size	32 byte CBR Payload
Terrain &	150X150 m^2
Nodes	100 nodes
Placement	Uniform
W_P & W_R	$W_P = 2$ & $W_R = 1$ in equation (1)

We expect typical communication patterns inside a sensor network to be established based on request and retrieval semantics for data delivery between sensor nodes and a querying entity. One-to-one, many-to-one and many-to-many communication patterns are representative workloads in sensor networks. One-to-one communication happens when one node detects some activity that needs to be reported to a remote entity. Alternatively, a querying entity will require periodic reports from the whole sensor area, which take the form of many-to-one communication. It is more common that multiple applications run simultaneously and the traffic flows interleave with each other, which is a many-to-many cross-traffic pattern. We evaluate 120 system configurations under different traffic loads, node mobility and energy conserving schedules. For each configuration we average 60 runs with different random seeds (hence 60 different network topologies and node placements) to ensure adequate confidence of our results. The 90% confidence interval is within 3% to 10% of the mean for GPSR and IGF, and 8% to 20% for LAR and DSR. Due to the space limitation, we only present results related to the more complex and interesting many-to-many scenario ($40 \times 60 = 2400$ runs). The complete data set is available upon request. In many-to-many cases, 6 nodes, randomly chosen from the left side of the terrain, send 6 CBR flows to 2 nodes (3 flows each) at the right side of the terrain. The average hop count is about 4~6 hops.

We note that most well-known sensor network protocols such as Directed Diffusion [7], TTDD[2] [23] and TBF [12] are mostly designed for static sensor networks and never evaluated in mobile environments. For the sake of fairness, we choose the only protocols that evaluate the mobility extensively in related publications ([1] [8] [10] [11]). Moreover, since few sensor network protocols deal with mobility, to reflect the broadness of the comparison, we choose both ad hoc and sensor network protocols. Specifically, 1) DSR [8] is a classical routing protocol for ad hoc mobile networks. 2) LAR [11] is a protocol optimized for mobility and is suitable for sensor network. And GPSR [10] is the standard location-based sensor network protocol with the greedy and planar perimeter forwarding rules.

We consider them in three scenarios:

(1) **A Static Network**, where nodes are not mobile and energy conservation is not considered;

(2) **A Mobile Network**, with mobility ranging from walking to vehicular speeds;

(3) **An Energy Conservation Network** where nodes can switch to dormant states.

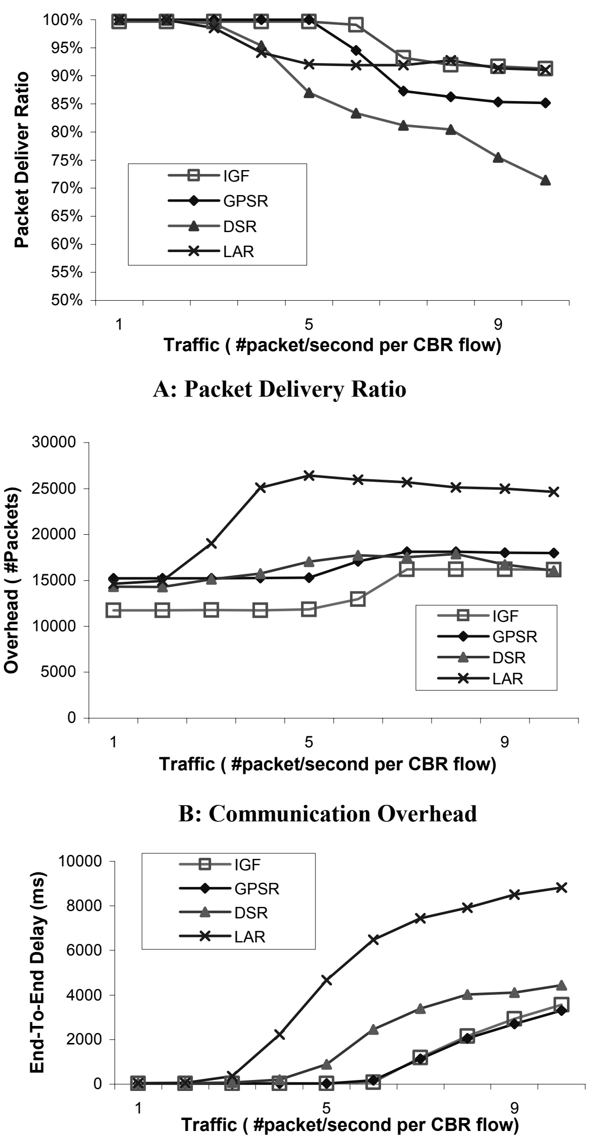
For each experiment we choose well established metrics on 1) the *Delivery Ratio* (number of packets received / number of packets sent), 2) average end-to-end *Delay* of received packets, and 3) overall communication *Overhead* (total packets sent at the Radio layer).

[2] TTDD delivers data to multiple mobile sinks such as PDA, while the nodes inside the sensor network are stationary

In addition to above experiments, we also evaluate the performance sensitivity of IGF in the presents of low node density (void) and localization errors in section 4.5 and 4.6, respectively.

4.2 Performance in Static Networks

The evaluation in static networks shows that IGF performs as well as or better than GPSR, DSR, and LAR, even when dynamics such as mobility and energy conserving sleep cycles are not considered. In these experiments, many-to-many CBR flows are simulated, increasing the flow rate until sufficient congestion is seen.



A: Packet Delivery Ratio

B: Communication Overhead

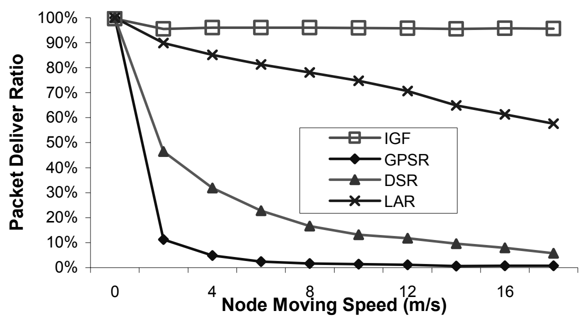
C: End-to-End Communication Delay

Figure 5: Performance in static networks

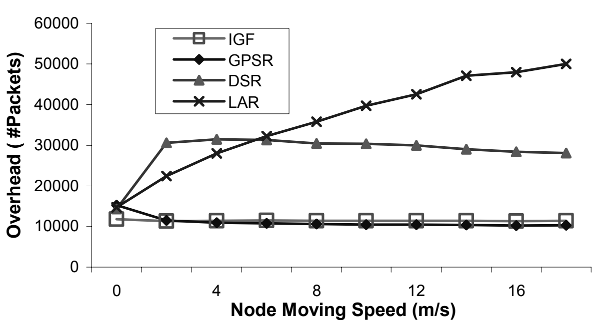
Figure 5A shows that GPSR and IGF have comparable delivery ratios under light loads, while LAR and DSR lose packets early as these protocols quickly congest the network by sending route discovery packets. When traffic flow rates increase enough to adequately congest the network in GPSR and IGF (6+ packets/second per CBR flow), performance in GPSR degrades due to limited intersecting routes, suffering additional collision caused by neighbor table update beacons (0.1 beacon per second). LAR uses location information to keep the effects of route discovery to a minimum allowing it to maintain delivery ratios comparable to IGF. However, LAR's frequent transmission of route discovery packets toward the destination, coupled with the latency incurred awaiting the route discovery response, lead to significantly more overhead (Figure 5B) and longer Delay (Figure 5C) when compared with IGF. Figure 5B demonstrates IGF's savings at low traffic loads, as IGF does not require beaconing (GPSR) or route discovery packets (DSR, LSR) required in these protocols. As traffic loads increase, congestion increases the number of MAC layer collisions in both IGF and GPSR, resulting in retransmission attempts that add to overhead shown in Figure 5B. For DSR, the overhead actually diminishes a little bit (Figure 5B) because more packets are dropped early. In GPSR and IGF we see significantly lower end-to-end delay beyond 4 packets/second per CBR flow because DSR and LAR suffer latency awaiting the return of route discovery packets. This effect becomes less apparent in DSR under heavy traffic because DSR's low delivery ratio leads to fewer packets contributing to this metric. Finally, under heavy traffic, we see a slightly longer delay in IGF over GPSR due to the fact that IGF manages to deliver 10% more packets (Figure 5A). We also note that Figure 5C demonstrates that the CTS back-off delay (tens microsecond in the worst case) due to lazy binding in IGF has virtually no impact on the end-to-end delay.

4.3 Performance under Mobility

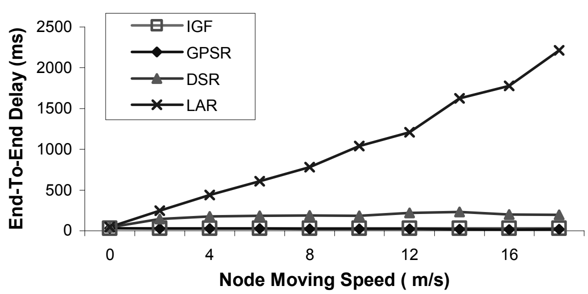
A scenario for this evaluation is a group of mobile robots equipped with magnet sensors are searching for mines in a battlefield. They report the detections to a base by relaying packets among themselves. We choose a standard waypoint mobility model during the simulations. It should be noted that different from ad hoc networks where the mobility pattern is interleaved with burst movements and long pauses, sensor robots are normally continuously moving. To reflect this scenario, we set only a 1-second pause time between moves (100~1000s pause time are normal settings in ad hoc network evaluations [1]). The setting will stress-test the protocols' capability to deal with continuous high mobility and reflect the mobility patterns seen in mobile sensor networks. We model speeds[3] up to 18 meters per second (~40 mph) to evaluate performance from slow robot speeds to vehicular speeds. Traffic is set at a rate of 1 packet/second per CBR flow to prevent congestion and therefore isolates the effects of mobility in our analysis. In these experiments source and intermediate nodes are mobile; however, we anchor destination nodes as a fixed base station.



A: Packet Delivery Ratio



B: Communication Overhead



C: End-to-End Communication Delay

Figure 6: Performance under mobile networks

In the static network scenario (section 4.2), we use a low beacon rate (0.1 beacon per second) in GPSR to reduce the effect of congestion, Here to optimize GPSR to deal with mobility, we test GPSR with multiple beacon rates. Because beacons consume bandwidth, their cost offsets their savings, arriving at similar results in all beacon rates we tested. Consequently, we adopt 1 beacon per second to keep the state as fresh as possible without causing congestion.

From Figure 6, we see that when nodes do not move (0 m/s), no packets are lost and the lowest Delay and Overhead are incurred due to minimal congestion. As we introduce mobility, increasingly affecting the validity of neighborhood and routing state with increased node speeds, we see the delivery ratios (Figure 6A) in GPSR, DSR, and LAR drop off quickly while IGF continues to perform close to optimum. For example, when the node moving speed is at 4 meters/second, IGF demonstrates more than 1000% of performance gain than GPSR and about 300% than DSR. For DSR and LAR, performance degrades as node migration invalidates eager-binding routes. Since LAR is specially designed to deal with mobility, its milder degradation, seen in Figure 6A, results from location controlled flooding of route discovery packets that reestablish routes despite mobility. In contrast, DSR's uncontrolled flooding and repeated route maintenance prevent DSR from establishing a stable route to the destination. The overhead for DSR (Figure 6B) therefore increases slowly because fewer transmissions are attempted as a result of packet loss.

As an addendum to explain why GPSR performs so poorly, we note from Figure 6A that GPSR's Delivery Ratio quickly drops to zero at relatively low node speeds. One might assume this is because the beacon overhead leads to congestion in GPSR, hence a very low delivery ratio. However, from Figure 6B, we note that control overhead in GPSR is actually smaller than DSR and AODV. In fact, this low delivery ratio in GPSR happens because according to greedy forwarding rules in GPSR, the chosen next-hop node normally is located at the edge of the sender's communication radius. Because nodes are equally likely to move toward any direction, theoretically there is more than 50% chance that the designated receiver will have moved out of communication range from the sender since the last beacon which is received ***seconds*** ago (see appendix A for the proof). Over multi-hop path the chances of failure grow exponentially (e.g. the chance of a broken link for GPSR under relative high mobility is 96.875% over 5 hops). In contrast, IGF binds a node **ten of microseconds** before the packet forwarding happens. Hence, the chance that the chosen node moves out of the communication range during this tiny interval is extremely slim.

Besides the delivery ratio (Figure 6A), the evaluation shows that IGF significantly outperforms other protocols in overhead (Figure 6B) and end-to-end delay (Figure 6C)

[3] Note that the degree of mobility is affected by both speed and radio range. With the same speed, a smaller radio range leads to a high mobility. We adopt a 40m radio range to confirm to current sensor ability, which is much smaller than 250m setting in [1] and [10] , which confirms to WLAN ability.

under all moving speeds. All these are due to IGF's ability to defer the mapping between routing states and network topologies until this mapping is absolutely required. Lazy-binding dramatically reduces routing failures and state invalidation due to the mobility of nodes.

4.4 Performance under Energy Conservation

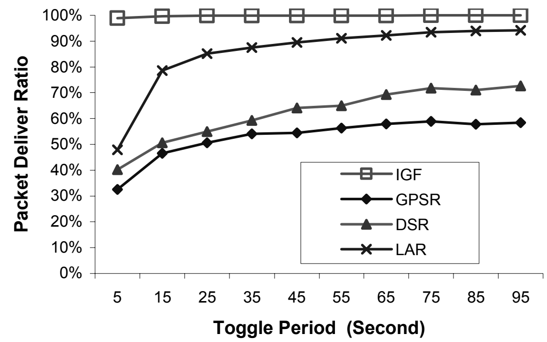
We test IGF, GPSR, DSR, and LAR in the presence of orthogonal energy conserving protocols by randomly transitioning nodes into and out of sleep states. To prevent congestion, and therefore isolate the effects of awake-sleep transition in our analysis, we set the flow rate to 1 packet per second. We note that two key parameters in energy-conserving protocols can affect the routing performance:

- **Toggle Period:** Toggle Period is the time interval between consecutive transitions into a sleep state. This parameter reflects how fast a routing state will be invalid due to the sleep-awake transitions. We range this value from 5 seconds, in step of 10, to 95 seconds.
- **Sleep Percentages:** The percentage of time a node is in sleep mode. We note that sleeping can significantly affect active node density, as this reduces the number of nodes participating in routing at any point in time.

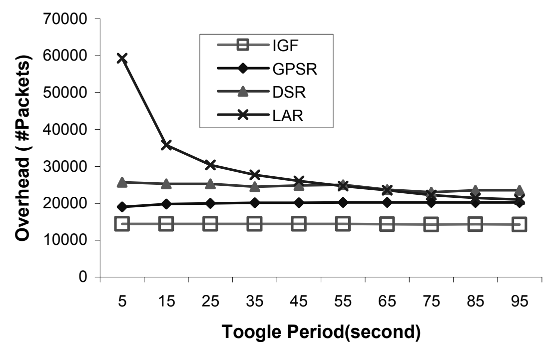
4.4.1 Performance under varied Toggle Periods

Figure 7A shows the results for many-to-many flows where the Sleep Percentage is set at 30% for varying Toggle Periods. It shows that IGF outperforms all other protocols at all toggle periods investigated. GPSR utilizes a beaconing mechanism to proactively bind network topologies into neighbor states. This binding can be quickly invalidated due to nodes' awake-sleep transitions. As a result, packets might be forwarded to nodes that were turned off since the last beacon and then dropped by the MAC layer. This leads to the poor delivery ratio in GPSR (Figure 7A). In DSR and LAR, a node requires the network layer to handle transmission failures by initiating route discovery (DSR, LAR). Due to the on-demand nature of those algorithms, DSR and LAR outperform GPSR, as the recently returned route discovery packet traverses nodes that are currently awake and therefore able to act as routers. DSR's performance is worse than LAR because of the bandwidth consumed during the less efficient route discovery process. Finally, we see IGF performing significantly better than other protocols, at times showing more than a 300% improvement in packets delivered when compared to GPSR. We attribute this superior performance to lazy-binding, utilizing whatever neighbors are currently awake en route to the destination.

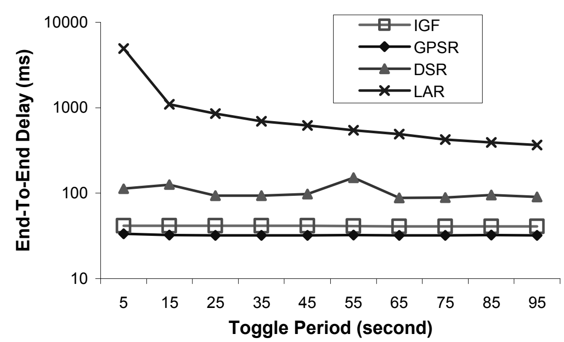
We note that the evaluation on the Toggle Periods here ranges from 5 ~ 95 seconds. When the Toggle Periods increase further, less dynamics are introduced into network topologies and routing states will be fresh for a longer period. Hence, higher delivery ratios are expected for other algorithms. Theoretically, when the Toggle Period approaches infinity, energy conserving networks become traditional static networks, for which we have shown the performance comparisons in section 4.2.



A: Packet Delivery Ratio



B: Communication Overhead

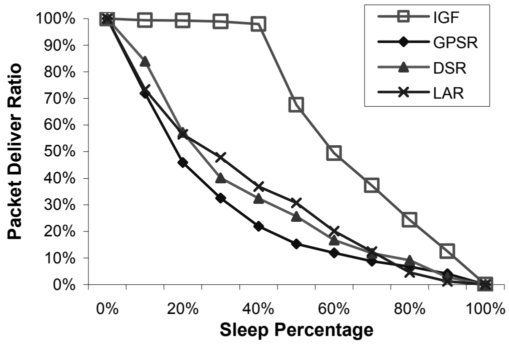


C: End-to-End Communication Delay

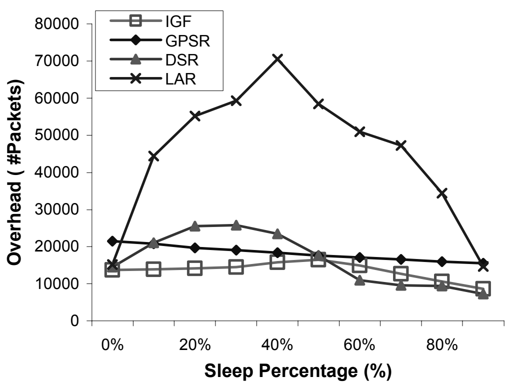
Figure 7: Performance under varied Toggle Periods

4.4.2 Performance under varied sleep percentage

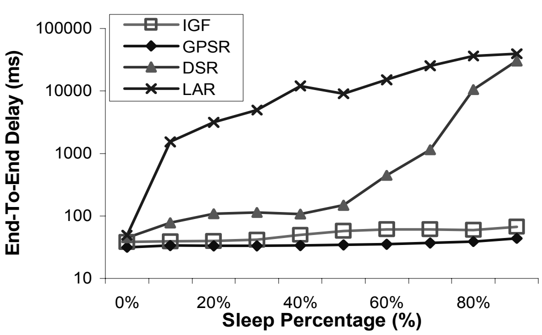
We next assess routing performance varying the Sleep Percentage for the high volatile case where the Toggle Period is set to 5 second. This not only allows us to compare our work under varied Sleep Percentage times, but allows us to stress test our protocol under high dynamic system settings. In this experiment, we increase sleep percentage of each node from 0% (always awake) to 100% (always asleep) in steps of 10%.



A: Packet Delivery Ratio



B: Communication Overhead



C: End-to-End Communication Delay

Figure 8: Performance under Varied Sleep Percentage

Figure 8A, B, and C all demonstrate IGF's excellent performance over varied Sleep Percentages. Figure 8A shows that IGF delivers the highest percentage of packets under all Sleep Percentage settings, while incurring the small end-to-end Delay (Figure 8C) and the lowest transmission overhead (Figure 8B). For example, Figure 8A shows that at a 50% sleep percentage, IGF delivers 340% more packets than the GPSR protocol. The marginally higher overhead of IGF than GPSR at above 60%+ level, shown in Figure 8B, is a result of GPSR achieving extremely low delivery ratio. The drastic drop in Overhead (Figure 8B) seen in LAR also is attributed to this drop in the Packet Delivery Ratio. Since DSR and LAR are designed to adapt to occasional node failures, as we expect, in such high dynamic networks, it take a huge end-to-end delay to fix the routes repeatedly (Figure 8C). GPSR shows a lowest end-to-end delay (Figure 8C) because it delivers a tiny percentage of packets compared to the IGF. Those packets go through the networks quickly by chance. Only IGF has a highest delivery ratio and a small delay. This because IGF can immediately detect nodes' transition into a sleep state and immediately utilize recently awoken nodes, thanks to lazy-binding.

4.5 Density Impact

In this experiment, we investigate the impact of node density on the IGF routing performance. To prevent congestion, and therefore isolate the effects of density in our analysis, we set the per flow rate to 1 packet per second. To change the density of the network, instead of increasing the number of nodes in the terrain, we keep the number of nodes constant at 100, and increase the side length of the square terrain from 100 meters, in steps of 20 meters, to 300 meters.

Figure 9 shows that with the forwarding area shift technique, IGF achieves 100% delivery ratio as long as the node density is larger than 10 nodes per nominal radio range. We acknowledge that while IGF is designed to deal with high dynamics in sensor networks, GPSR-like extension should be added into the IGF protocol to achieve the same performance as GPSR (Figure 9).

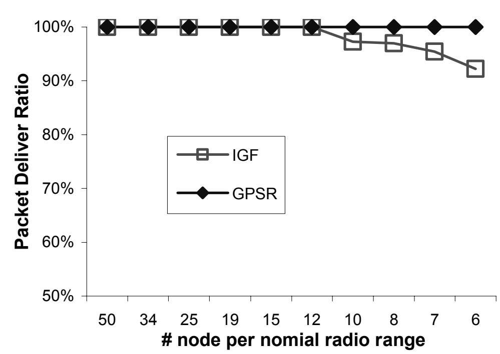


Figure 9: Delivery Ratio Under Varied Node Density

4.6 Location Error Impact

While most work in location-based routing assumes perfect location information, the fact is that erroneous location estimates are virtually impossible to avoid. In this experiment, we investigate location error impact on the IGF protocol. To prevent congestion, and therefore isolate the effects of localization error, the traffic load are set to rate of

1 packet/second. We increase the localization error from 0% to 50% of the radio range in steps of 5% to measure the end-to-end delivery ratios. Figure 10 demonstrates that both the IGF and GPSR protocol perform well in the presence of localization errors while the basic geographic forwarding with the greedy forwarding rule suffers when such errors increase.

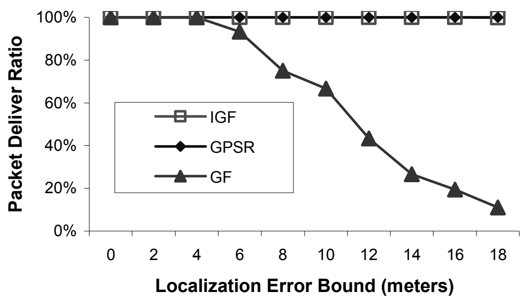


Figure 10: Localization Error Impact

4.7 Experiment Conclusions

In our experiments we assess the performance of IGF compared to DSR, LAR, and GPSR under 7200 different configurations. We use delivery ratio, transmission overhead, and end-to-end delay as our metrics for comparison. For the static network experiment, we vary the network workload demonstrating that IGF performs as well as or better than GPSR, DSR, and LAR at varied levels of congestion. We then run similar tests under a light workload to assess IGF's abilities when considering mobile nodes. We find that continuous mobility severely influences the eager-binding routing protocols as neighborhood and routing tables require constant repair. In contrast, mobility barely reduces IGF's performance, thanks to IGF's lazy-binding and state-free properties. Finally, we evaluate sensor network systems where nodes make transitions into dormant states to conserve energy. Under varied Toggle Periods we demonstrate that IGF outperforms other solutions by as much as 300% at some toggle period. We also demonstrate IGF's superior performance under varying Sleep Percentages. We have done extensive test on IGF in static, highly dynamic mobile, and energy conserving scenarios under a large range of configurations, and we expect similar results to follow for alternate scenarios.

5. IMPLEMENTATION ON MOTES

We have implemented a prototype of the IGF protocol on the Berkeley motes platform [21] with a code size of 11,606 bytes (code is available through CVS at [anonymous]). Currently, this version is built on top of a MAC protocol with the implicit ACKs mentioned in section 3.4.4. Three applications including data placement, target tracking and CBR data streaming are also built to run on top of IGF. Due to the physical constrains and the un-availability of protocols proposed in the literature on such a platform, it is difficult to perform as extensive evaluation as we did in the wireless simulator. As a result, we only present initial results on here as a study in developing a more complete solution and evaluation in the future mote platform.

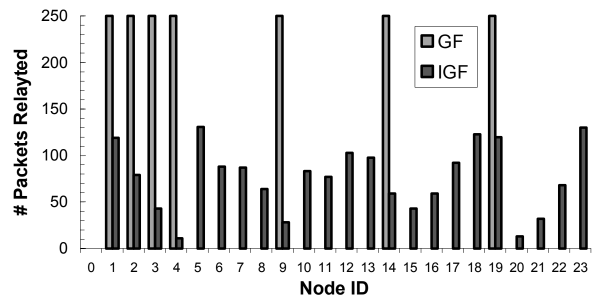


Figure 11: Traffic Balance

As we mentioned in section 3.1, IGF does not task a specific node beforehand, this feature is beneficial for the load balancing among the nodes inside the forwarding area. In the experiment, we use 25 motes to form a 5 by 5 grid. To evaluate the load balancing capability of IGF we send a CBR data stream from node 24 to node 0 which is the base station. We collect the number of packets relayed by intermediate motes (1~23) and compare this with the result obtained from the GF protocol which we also implemented on the motes. While both GF and IGF achieve nearly 100% delivery ratio, GF tends to relay packets via a fixed route which might leads to unbalance traffic, for example, in Figure 11, node 19 relays 250 packets while node 18 doesn't forward any packets. In stead, IGF can balance energy consumption. We argue that in sensor networks, balanced energy consumption can prevent some nodes from dying faster than others, therefore increasing the network lifetime.

6. RELATED WORK

In this section we discuss prior research in distributed computing that is pertinent to the design of IGF.

Various protocols have been introduced to reduce packet loss through reliable communication in sensor networks. RMST [15] tracks packet fragments so that receiver initiated requests can be satisfied when individual pieces of an application payload get lost. PSFQ [19] caches packets along the path to the sender, initiating fragment recovery as required, starting with its local neighborhood. Robust data delivery [4] simultaneously sends packets along multiple paths at the expense of increases in communication overhead. While these ARQ/FEC-based solutions have proven effective when dealing with interference and collisions, their robust and reliable features can not handle failures due to high dynamics in network topologies. We consider them orthogonal and complementary to our work.

Many routing algorithms have been proposed for ad hoc and sensor networks. With regard to the mechanisms used to bind network topology to the routing state, we divide these routing protocols into three categories.

The first category we term as *proactive eager-binding* routing algorithms. DSDV [13] requires each node to proactively broadcast routing updates periodically. Global routing tables are refreshed regardless whether there is need of data delivery. Location-based routing algorithms such as GPSR [10] remove the requirement that a protocol maintains a global view of the network (i.e. end-to-end routing tables), therefore reduces communication overhead by eliminating its dependence on network wide state information. However, they still depend on up to date local neighborhood tables, requiring control overhead to maintain and suffering latency and packet loss when a node's neighborhood state changes between updates

To minimize unnecessary overhead incurred by proactive updates, a set of on-demand algorithms are proposed to defer route acquisition until data delivery is required. We term the second category as *reactive eager-binding* algorithm. It has been proved in [1] that AODV [14] and DSR [8] can successfully deal with moderate mobility with long pause intervals (100 ~ 1000 seconds). However, the eager binding of routing state at the route acquisition phase make them ineffective to deal with high dynamics in which network topologies change at a much faster rate than the duration of connections. Routing maintenance and rediscovery are proposed in [8] [14] to partially remedy this problem at the cost of higher delay and expensive control overhead. LAR [11] extends the on-demand idea proposed by AODV [14] and DSR [8], utilizing location information to limit the scope of route requests. While LAR significantly reduces routing overhead by only propagating queries to relevant portions of the network, it still needs to maintain or establish an explicit path prior to transmitting a packet.

Current reactive eager-binding algorithms can successfully deal with occasional node failure and moderate mobility. However, the elevated dynamics due to continuous mobility and power conservation inside sensor networks challenges us to develop a new category of routing protocols based on lazy binding concept with superior performance over pervious solutions. The first state-free protocol IGF belongs to this third category.

7. CONCLUSIONS

In highly dynamic sensor networks, the maintenance of freshness of routing states is costly. The state update, due to eager-binding, contributes to network congestion, wasting precious energy, and introduces end-to-end transmission latency. To prevent the adverse affects that dynamic factors such as high mobility have on state-based eager-binding routing protocols, we advocate a novel concept of lazy-binding to cope with high dynamics in sensor networks. Base on this concept, we introduce IGF, the first protocol that altogether state-free. In simulation we compare our work against protocols designed for mobile environments and sensor networks. IGF demonstrates more than 1000% improvement in the packet delivery ratio when the sensor network is highly mobile and it also achieves significant reduction in delay and overhead when considering mobility and energy-conservation, proving the lazy-binding's capability to cope with high dynamics found inside wireless sensor networks. In addition, a prototype of the IGF protocol has been implemented on the Berkeley motes platform to serve as an initial study in developing a more complete solution in the future.

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APPENDIX A

Problem Definition: Suppose the nominal radio range is R feet, the nodes move at a constant speed S feet/second and the direction of the movements are uniformly distributed in $[0,2\pi)$. For two nodes A and B that are r feet ($r \le R$) away from each other, find out the probability $P(t)$ that node B moves out of node A's radio range in the duration of t. (suppose both nodes do not change the directions during the interval t)

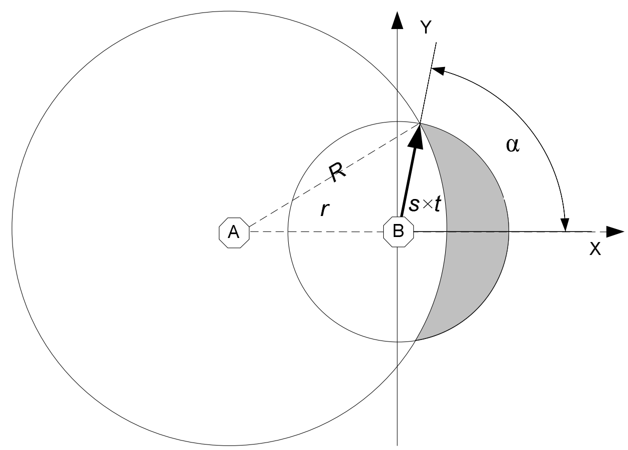

Figure 12 Boundary Condition of link break

Solutions: The speed vectors for node A and node B can be denoted by the polar coordinates (S, θ_A) and (S, θ_B), in which S is the constant speed and θ_A and θ_B are the directions of movements that follow a uniform distribution in $[0,2\pi)$. Without loss of generality, assume A is static, the relative speed of node B with respect to node A is (s, α) in the polar coordinate. According to [5], α maintains a uniform distribution in $[0,2\pi)$. As shown in Figure 12, node B moves out of node A's communication range, iff the trajectory of node B intersects with A's radio circle during the interval t. As shown in Figure 12, the boundary condition happens when node B reach A's circle at the end of interval t. In boundary condition, α can be calculated by Equation (2):

$$\alpha = \begin{cases} \pi - \arccos\dfrac{r^2 + (s \times t)^2 - R^2}{2r \times s \times t} & s \times t < r + R \\ \pi & s \times t \ge r + R \end{cases} \quad (2)$$

When node B has a relative speed vector with the angular coordinate belonging to [0, α] or [$2\pi - \alpha$, 2π), it moves out of node A's range. Since α follows a uniform distribution in [0,2π), for give speed s, the $P(t)_s$ satisfies:

$$P(t)_s = \frac{\alpha}{\pi} \quad (3)$$

Integrating $P(t)_s$ over relative speed s from zero to $2S$, the $P(t)$ can be calculated according to Equation (4):

$$P(t) = \int_0^{2S} \frac{\pi - a\cos\left(\frac{r^2 + (s \times t)^2 - R^2}{2r \times s \times t}\right)}{\pi} p(s)ds \quad (4)$$

$$when \quad s \times t < r + R \quad or \quad P(t) = 1 \; when \quad s \times t \geq r + R$$

Where $p(s)$ is the probability distribution function (PDF) of the relative speed s.

We can obtain the close form of $P(t)$ by using PDF of s by Bennett [1], however here we are only interested in the special case where $r = R$. In this case, Equation (4) simplifies to (5):

$$P(t) = \int_0^{2S} \frac{\pi - a\cos\left(\frac{(s \times t)}{2r}\right)}{\pi} p(s)ds \quad (5)$$

$$when \quad s \times t < 2R \; or \; P(t) = 1 \quad when \quad s \times t \geq 2R$$

Since $a\cos(\frac{(s \times t)}{2r}) \leq \frac{\pi}{2}$, from equation (5) we get inequality (6) as follows:

$$P(t) \geq \int_0^{2S} \frac{1}{2} p(s)ds = \frac{1}{2} \quad when \quad r = R \quad (6)$$

Inequality (6) denotes that when node B locates at the edge of node A's radio range, regardless of the node's speed s and the duration of movement t, the chance of link break between node A and node B is lager than or equals 50%. Actually, $P(t)$ monotonically increases with the speed s and the duration t. For the case of the GPSR protocol which uses the greedy forwarding rule when possible, it chooses the node that is nearest to the edge of the radio range. Theoretically, if the network is dense, it has more than 50% chance to experience the link break during the forwarding in the presence of mobility. On the other hand, IGF binds the next-hop on the fly, utilizing the nodes currently available, and hence dramatically reduces the chance of link break.